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A Methodology for Battle Damage Repair (BDR) Analysis

Lisa K. Roach

ARL-TR-330

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With the down-sizing of the military services and the emphasis on maintaining current systems, the area of battle damage repair (BDR) is receiving renewed focus at all levels. Evidence of this is the inclusion of maintainability/BDR requirements in the Department of Defense (DoD) Directive 5000.1, and DoD Instruction 5000.2. Unfortunately, methodologies to assess the impact of BDR on individual system performance or to perform BDR trade-off analyses are not well developed or documented.

As an extension of the general vulnerability/lethality (V/L) process structure, the Ballistic Vulnerability/Lethality Division (BVLD) of the U.S. Army Research Laboratory (ARL) has developed a methodology to perform analyses of the effects of BDR on an individual system's performance. Furthermore, a separate undertaking by BVLD will permit the inclusion of BDR analysis in force-level models such as JANUS and CASTFOREM.

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I. Introduction

With the build-down of the military services and the emphasis on maintaining current systems, the area of battle damage repair (BDR) is receiving renewed focus at all levels. Evidence of this is the inclusion of maintainability/BDR requirements in the Department of Defense (DoD) Directive 5000.1 and DoD Instruction 5000.2. Unfortunately, methodologies to assess the impact of BDR on individual system performance or to perform BDR tradeoff analyses are not well developed or documented. Additionally, there is no uniform treatment of repair across the services, or even across mission areas within the U.S. Army. Consequently, a standard accounting of the consequences of various levels of repair is not currently possible.

As an extension of the general Vulnerability/Lethality (V/L) Process Structure, the Ballistic Vulnerability/Lethality Division (BVLD) of the U.S. Army Research Laboratory (ARL) has developed a methodology to perform analyses of the effects of BDR on an individual system's performance. Furthermore, a separate undertaking by the BVLD will permit the inclusion of BDR analysis in force-level models such as JANUS.

II. Background

1. The V/L Process Structure (Taxonomy)

To understand the BDR methodology, one must first understand the V/L Process Structure, first defined by Deitz (1989) and refined by Walbert and Roach (1993), and the Degraded States Vulnerability Methodology (Abell, Roach, Starks 1989), (Abell, Burdeshaw, Rickter 1991). A brief discussion is provided here.

The basis for the taxonomy of V/L Spaces comes from the recognition that V/L analyses pass through distinct levels of information in a precise order. These levels are:

Level 1: Threat-Target Interaction, or Initial Configuration
(including Initial Conditions),

Level 2: Target Component Damage States,

Level 3: Target Capability States, and

Level 4: Target Combat Utility.

From the Target Capability States can be derived the various mission-oriented losses of function such as "Firepower Loss of Function (LOF)" and "Mobility LOF".

The mappings by which one passes from one level to the next are dependent on different kinds of information at each level. For example, going from Level 1 to Level 2 (threat-target initial configuration to target damage) essentially involves physics; going from Level 2 to Level 3 (target damage to capability) requires engineering measurement. The process is shown pictorially in Figure 1.

It is important at the outset to differentiate between "Levels", which are composed only of states of existence, and the "mappings", operators -- with the data and algorithms to which they have access -- which relate a state at one level to a state at another.

A *Level* contains all the information required to define the state of the system at the associated stage of a V/L analysis/experiment. At each level, one can define a space of points, each point being a vector whose elements correspond to the status of a particular entity related to the target. For example, in Space 2 (Damage States), each element may refer to the status of a particular component/subsystem. The spaces thus defined are the "V/L Spaces", and represent, at each level, the state of the target system.

A *Mapping* represents all of the information (physics, engineering, etc.), known or unknown, required to associate a point in a space at one level with a point in a space at the next level. Mappings have access to information such as: fundamental data (penetration parameters [Level 1 to Level 2], leakage rates [Level 2 to Level 3], etc.); intermediate data generated by the mapping (line-of-sight thicknesses [1 to 2], temperature rise in an uncooled engine [2 to 3]); and algorithms (depth of penetration [1 to 2], fault trees [2 to 3] or [3 to 4]).

The V/L experimental and analytical processes can then be expressed as a series of mappings which relate a state vector in one space (the domain) to a resultant state vector in a next higher-level space (the range).

Note that at each transition to the next level, some detail about the target system may be lost: a broken bolt in Level 2 may be the cause of degraded mobility influencing mission effectiveness, but at Level 3, the bolt is no longer recognized as an entity. It is now widely acknowledged that skipping over levels (such as inferring remaining combat utility directly from the size of the hole in the armor) loses so significant an amount of information that continuity and auditability are lost.

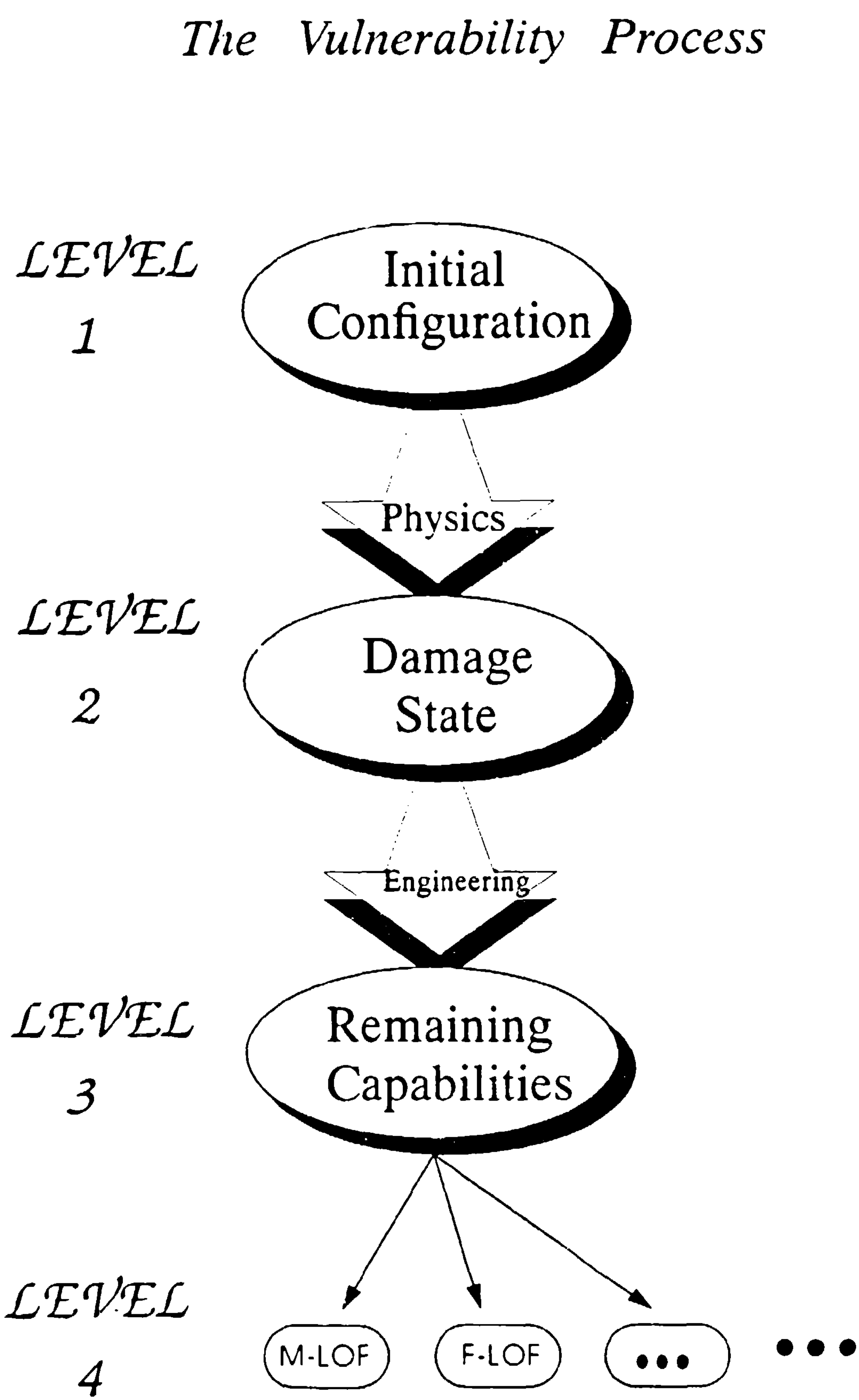

Figure 1. The Vulnerability/Lethality Process Structure

2. Degraded States Vulnerability Methodology (DSVM)

The DSVM is an O2,3 methodology which maps the target damage state into its remaining capability state; it is this methodology, and the damaged component information at Level 2, which allows the development of the BDR methodology. As an example of the DSVM, an armored fighting vehicle's required capabilities could be described in terms of a six-element vector (Mobility, Firepower, Acquisition, Crew, Communications, Ammunition). Conventional Degraded States (DS) terminology refers to these elements as "capability categories"; each DS capability category is further divided into capability levels which define a particular performance degradation (i.e. reduced speed, reduced accuracy, etc.). Included within a capability category are all possible combinations of capability levels that could occur simultaneously and a "no damage" capability level. These two properties of the capability category make the capability levels within a category both mutually exclusive and exhaustive. For any set of components, one and only one capability level will be satisfied for each capability category. This combination of capability levels, one from each category, represents the degraded state of the vehicle.

Mathematical fault trees are developed to represent the components and/or subsystems which contribute to the capability levels in each capability category (or element of the VL3 vector). These fault trees consist of a list of critical vehicle components that, if killed, result in that particular capability level being satisfied. For a particular capability category, a capability level achieved when no uninterrupted path can be traced from top to bottom in the fault tree. The fault tree path configurations can be described as having components arranged in series or in parallel or as some combination of the two. If listed in series, the loss of any component causes an interruption in the path whereas those components listed in parallel must all be killed to interrupt the path. The components listed in the fault trees can represent either a single critical component or a system of critical components. The systems of components are usually developed into fault tree configurations during the criticality analysis. [Note, a criticality analysis is a process where a fully functional combat system is analyzed system by system to determine which ones contribute directly to mission functions. Each system is described via a fault tree and, as indicated, is basically the determination of 1) which components, if lost, might result in a reduction of system capability, and 2) the structuring of these "critical" components into a fault tree format.]

III. BDR Methodology

Figure 2 depicts the structure behind the BDR methodology, laid out in terms of the V/L taxonomy. Battle damage repair, or any kind of repair, can be modeled using the V/L Process Structure approach in the following manner. Given an initial set of component damage at Level 2, a mapping can be performed (using the DSVM) to determine the remaining capabilities of the system

at Level 3. This represents the capability of the system given no repair is performed. If one can establish repair priorities and required repair times, one can perform a sensitivity analysis to determine the usefulness of repairs by attempting to do whatever repairs are possible in the allotted time. This provides a second set of damaged components, one which is (possibly) a subset of the original set. Using this new damage component vector (Level 2), a mapping is performed again to determine the remaining capabilities of the system given the affected repairs. After a comparison is made between the original set of remaining capabilities and the new set resulting from repair, an assessment can be made of the usefulness of the repairs, i.e., what did it gain the system in terms of capabilities.

A series of repairs can be identified, and sensitivity analyses performed, to determine what capabilities the system gains as a result of varying amounts of repair time and parts stockage. These analyses can indicate what repairs are necessary in terms of system performance, what types of spare parts need to be stocked and what the critical path is in terms of needed repair. It should be noted that when the repairs are attempted a system may remain at the same damage point as the one before repairs were affected, i.e., not enough time was allocated. Conversely, a system may be returned to fully functional if all the damaged components were repaired. In addition, the sensitivity analyses may indicate whether or not the system can continue a certain mission, given the capabilities required are available.

Another way to view the BDR methodology is to start at Level 4 and ask the question, what is the system's mission and what capabilities are needed to accomplish it? This returns the system to Level 3 to determine whether or not the capabilities are available. If not, the path is traced back to Level 2 to determine what components are needed to permit the functioning of the capabilities required to accomplish the mission; this gives an indication of what components need to be repaired.

IV. A Simple Application of the BDR Methodology

To further illustrate, a simple example is provided. Information available from previous DSVM analyses of the M1A1 Abrams tank will be used (Abell, Roach, Starks, 1989), (Abell, Burdeshaw, Rickter, 1991). The capability categories and levels defined for the M1A1 DSVM analyses are provided in Table 1 while the fault trees representing these levels can be found in Appendix A. Assume the following components on the vehicle have been rendered nonfunctional, either due to combat damage or reliability failure: throttle steering housing, parking brake lock, laser rangefinder, and the breech mechanism assembly. The effect of these components, in terms of DSVM capability levels, is contained in Table 2 while the associated repair time for each component is listed in Table 3.

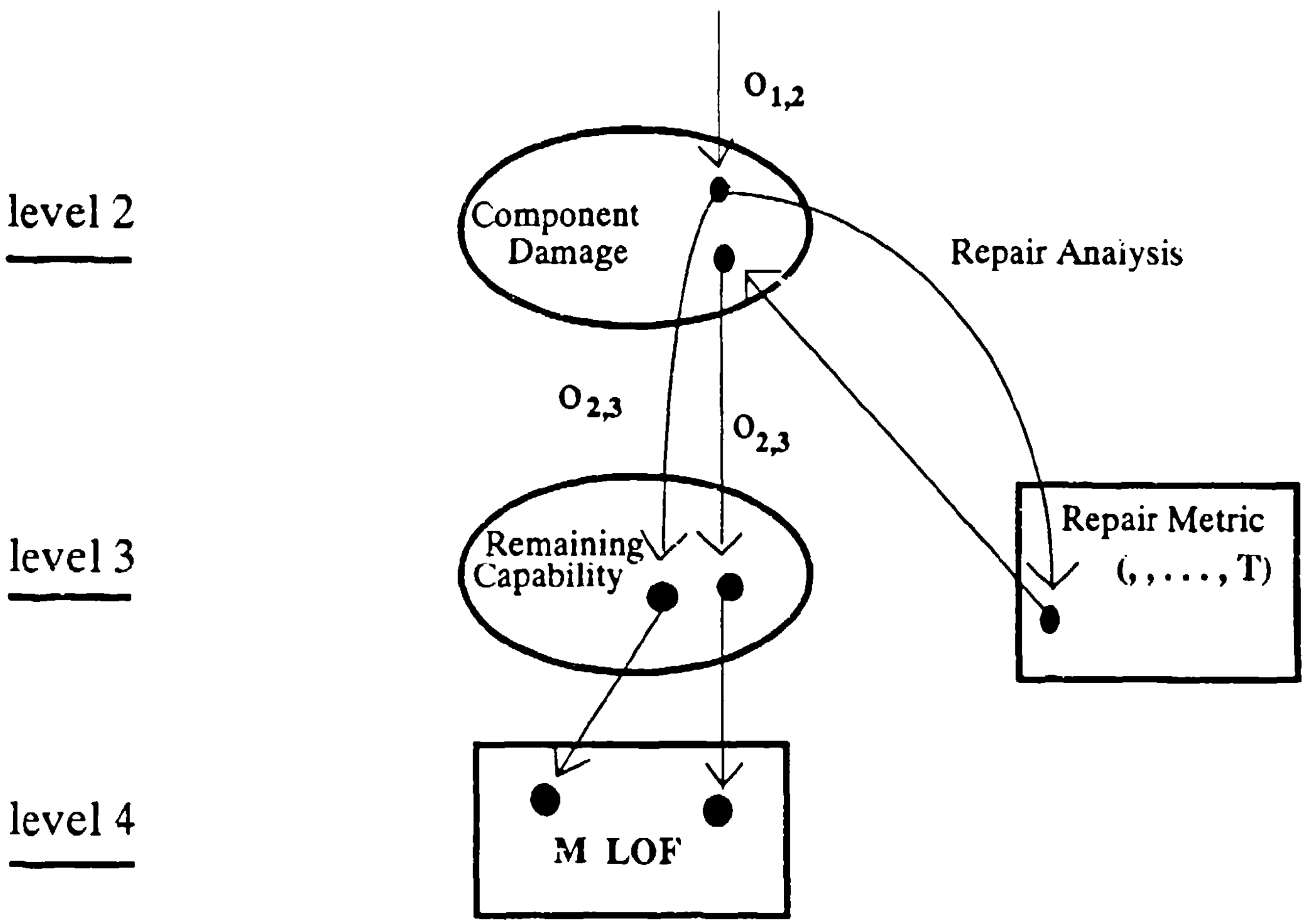

Figure 2. Proposed BDR Methodology

Table 1. M1A1 Degraded States Capability Categories and Levels

Mobility Capability Category

M0--> No mobility damage

M1--> Reduced speed (slight)

M2--> Reduced speed (significant)

M3--> Total immobilization

Firepower Capability Category

F0--> No firepower damage
F1--> Loss of main armament
F2--> Unable to fire on the move
F3--> Increased time to fire
F4--> Reduced delivery accuracy
F5--> Loss of secondary armament
F6--> F2 and F3
F7--> F2 and F4
F8--> F3 and F4
F9--> F2 and F3 and F4
F10--> F2 and F5
F11--> F3 and F5
F12--> F4 and F5
F13--> F2 and F3 and F4 and F5
F14--> F2 and F3 and F5
F15--> F2 and F4 and F5
F16--> F3 and F4 and F5
F17--> F1 and F5 (total loss of firepower)

Acquisition Capability Category

A0--> No acquisition damge
A1--> Reduced acquisition capability
A2--> Unable to acquire while moving
A3--> A1 and A2

Crew Capability Category

C0--> No crew casualties
C1--> Commander
C2--> Gunner
C3--> Loader
C4--> Driver
C5--> C1 and C2
C6--> C1 and C3
C7--> 1 and C4
C8--> C2 and C3
C9--> C2 and C4
C10--> C3 and C4
C11--> C1 andC2 and C3
C12--> C1 and C2 and C4
C13--> C2 and C3 and C4
C14--> C1 and C3 and C4
C15--> C1 and C2 and C3 and C4

Communications Capability Category

X0--> No communication damage
X1--> No internal communication
X2--> No external communication > 300 ft
X3--> No external communication
X4--> X1 and X2
X5--> X1 and X3

Ammo Capability Category

K0--> No ammo lost
K1--> Bustle ammo lost
K2--> Hull ammo lost
K3--> K1 and K2
K4--> K-kill

TABLE 2. Damaged Components Effects in Terms of DSVM Capability Levels

COMPONENT	CAPABILITY LEVEL
Throttle Steering Housing	M2 - Significant reduction in speed
	M3 - Total Immobilization
Parking Brake Lock	M2 - Significant reduction in speed
Laser Rangefinder	F1 - Loss of main armament
	F2 - Unable to fire on the move
	F3 - Increased time to fire
	F4 - Reduced delivery accuracy
	A2 - Unable to acquire while moving
Breech Mechanism Assembly	F1 - Loss of Main Armament

TABLE 3. Component Repair Times (in manhours)*

Component	Repair Time
Throttle Steering Housing	0.7
Parking Brake Lock	3.0
Laser Rangefinder	0.4
Breech Mechanism Assembly	1.2

*Technical Manual, Maintenance Allocation Chart - Tank, Combat, Full-Tracked: 120-MM Gun, M1A1 General Abrams , TM 9-2350-264-MAC, Headquarters, Department of the Army, February 1986.

1. Initial BDR Analysis

For the purposes of this example, it is assumed that all required spare parts are available and that the tank's organizational repair unit is nearby and can begin repairs immediately (thus, no time is lost awaiting repair personnel and spare parts). It is also assumed that the repairs will be performed sequentially, from shortest to longest time period. Since the laser rangefinder only requires 0.4 manhours, it is repaired first. Recall from Table 2, that the loss of this component causes the loss of most firepower capabilities, and some acquisition capabilities, of the tank. With repair, the F2, F3, F4, and A2 capabilities are

restored. However, the main armament (F1) is not as the breech mechanism assembly has yet to be repaired. After approximately 24 minutes, the tank has most of it's firepower and acquisition capabilities restored but still does not have the use of its main armament or its mobility capability. Repairing the throttle steering housing next, after 0.7 manhours, the tank is no longer totally immobilized but still has significant speed loss until the parking brake lock is repaired. Based on the repair times, the breech mechanism assembly is repaired next, restoring full firepower capability to the system. Finally, requiring 3.0 manhours of repair time, the parking brake lock is repaired, restoring the vehicle to full capability. Thus, if sequential repair is done, the tank is fully functional again after 5.3 manhours.

2. Additional BDR Sensitivity Analyses

If the assumptions are changed, then additional analyses may be conducted to give further insight into the problem. For example, if the repairs are done concurrently, it would require 3.0 manhours to restore the vehicle to full capability though some capabilities (such as the firepower and acquisition) would be restored earlier. One may also wish to examine only a subset of the needed repairs - those which would enable the system to continue it's current mission. For example, suppose our example tank was in an overwatch position, where mobility was not required. In this case, the repair of the parking brake lock and the throttle steering housing could be by-passed in favor of repairing the breech mechanism assembly and the laser rangefinder. These components would enable the tank to continue with it's assigned mission in less than 1.5 hours, assuming the time until mission continuance was reasonable. Of course, those components not repaired may affect the tank's ability to do other missions. If, for example, the tank must subsequently move, the parking brake lock and the throttle steering housing must first be repaired. This factor could also be considered.

Another area which lends itself to these types of analyses is spare parts requirements and stockage. With the O12 mapping, a series of damage vectors can be computed to infer a distribution for the likelihood of component damage. This information can then be used to determine wartime spare parts stockage for the different components. Additional analyses can be conducted comparing these wartime requirements with those currently computed for peacetime. Insights can be gained as to whether or not the wartime and peacetime requirements are similar and what types of components, and in what quantities, need to be stocked. If the system's capabilities are considered, one can concentrate on the components most likely needed for anticipated missions.

Finally, a more detailed application of this methodology will be discussed in a forthcoming ARL technical report. Under support of the U.S. Army Training and Doctrine Command (TRADOC)'s Ordnance Center and School Battle Damage Assessment and Repair (BDAR) office, the approach promulgated in this report was applied to existing damaged component information on the M1A1 tank and the usefulness of the methodology discussed.

V. Consistency with Other Analyses

An important side benefit to this approach is its comparability with other analyses performed in support of the acquisition process, namely, vulnerability/lethality (V/L) and reliability, availability, and maintainability (RAM). As stated above, the BDR approach is an extension of the general V/L process structure. Using the same structure for these analyses provides a common basis for comparison. All three analyses are concerned with non-functional components and their affect on system performance. The V/L process structure approach provides explicit information on the functionality of components (Level 2); it is immaterial how the component was rendered non-functional. This information is then directly related to system performance via the O2,3, mapping with remaining capability reported at Level 3. One can use this approach to study vulnerability or vulnerability reduction concerns, RAM requirements, and the affect of various repair considerations. By using the same approach for the three types of analyses discussed, a basis for comparison is provided throughout the acquisition cycle. The analyses are performed using the same methodology and the results are reported in the same metrics. This facilitates comparisons among these concerns at all junctures throughout the acquisition cycle.

VI. Use in Force-Level Models

Finally the introduction of DSVM metrics in force-level models will permit explicit consideration of BDR (and RAM) in these models. A current effort between the BVLD and the Training and Doctrine Command (TRADOC) Analysis Center at White Sands Missile Range (TRAC-WSMR) will enable the inclusion of BDR concerns in force-level models such as JANUS and CASTFOREM. Specifically, the BVLD and TRAC-WSMR are modifying the JANUS and CASTFOREM models to accept the DSVM metrics as well as store the damaged component vectors available from the O12 mapping. This work could be expanded to allow specific modeling of repair strategies and repair times.

The inclusion of the DSVM metrics and component information in these models will allow BDR to be played directly in the models and its affect on the systems and battle outcome to be measured directly. Specifically, the battle could be played several times employing various repair strategies, i.e., no repair, complete repair, and intermediate levels. The overall affect on battle outcome can

then be quantified and the usefulness of the various strategies measured. Suppose, using our example M1 tank again, we devise the following possible repair strategies:

1. No repair;
2. Repair breech mechanism assembly (1.2 hrs) and the throttle steering housing (0.7);
3. Repair breech mechanism assembly (1.2 hrs), throttle steering housing (0.7 hrs) and the laser rangefinder (0.4 hrs);
4. Complete repair.

The force-level model then could be run four times, playing these four strategies. Information could be gleaned on the affect of the repair on overall battle outcome, the timeliness of the repair, i.e., was it repaired in time to have an affect on the outcome, and which strategy made the most sense given mission of the tank. Further analyses could be performed using information on wartime parts stockage; one could examine spare parts availability given the selected repair strategy.

Note, the BVLD/TRAC-WSMR effort provides the groundwork for eventually performing these kinds of repair analyses. Additional work on JANUS and CASTFOREM, beyond the current undertaken, would be required to make repair analyses a reality within these force-level models.

VII. Summary

Currently, there is no uniform treatment of repair across the tri-services or even across combat arms within the Army. The BDR methodology presented in this report solves the problem and provides auditability and consistency of results. It also provides an approach whereby a standard accounting of consequences, in terms of performance and cost, of various levels of repair can be determined; this permits uniform comparisons across the mission areas.

As this report indicates, there are a number of analyses that can be performed. One can investigate concurrent versus sequential repair priorities and organizational versus crew repairs; one might also investigate expedient repairs that may enable the vehicle to continue more quickly its current mission. Additionally, the problem of peacetime versus wartime spare parts stockage requirements can be addressed in detailed. Furthermore, analyses can be performed investigating the full gamut of repairs, or concentrating only on those repairs which will allow continuation of a given mission.

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